

MULTI PUMPING CHAMBER MAGNETOSTRICTIVE PUMP

FIELD OF THE INVENTION

[0001] The present invention relates generally to pumps,
5 and more particularly to pumps making use of
magnetostrictive actuators.

BACKGROUND OF THE INVENTION

[0002] Conventional positive displacement pumps pump
10 liquids in and out of a pumping chamber by changing the
volume of the chamber. Many pumps are bulky with many
moving parts, and are driven by a periodic mechanical
source of power, such as a motor or engine. Often such
pumps require mechanical linkages, including gearboxes, for
15 interconnection to a suitable source of power.

[0003] Other types pumps, as for example disclosed in US
Patent No. 5,641,270; and German Patent Publication No. DE
4032555A1 use an actuator made of a magnetostrictive
material. As will be appreciated, magnetostrictive
20 material change dimensions in the presence of a magnetic
field. Numerous magnetostrictive materials are known. For
example, European Patent Application No. 923009280
discloses many such materials. A commercially available
magnetostrictive material is sold in association with the
25 trademark Terfenol-D by Etrema Corporation, of Ames, Iowa.

[0004] These magnetostrictive pumps rely on the expansion and contraction of a magnetostrictive element to compress a pumping chamber. Known magnetostrictive pumps however compress a single pumping chamber. As such, these pumps produce a single pumping compression stroke for each cycle of contraction and expansion of the magnetostrictive material. This, in turn, may result in significant pressure fluctuations in the pumped fluid. The flow rate is similarly limited to the displacement of the single pumping chamber. Moreover, pumps with a single actuator may be mechanically imbalanced and thereby prone to mechanical noise and vibration as the single actuator expands and contracts.

[0005] In certain applications, constant pressures and high flow rates per unit weight of a pump are critical. For instance, in fuel delivery systems in aircrafts, pump designs strive to achieve low pump weight to fuel delivery ratios, while still providing for smooth fuel delivery.

[0006] Accordingly, an improved magnetostrictive pump facilitating high flow rates, and smooth fluid delivery would be desirable.

SUMMARY OF THE INVENTION

[0007] In accordance with the present invention, a pump includes a magnetostrictive element, and multiple pumping chambers all driven by this magnetostrictive element. The pumping chambers may pump fluid in or out of phase with

each other.

[0008] Conveniently, a pump having multiple pumping chambers may provide for smoother fluid flow, less pump vibration, and increased flow rates.

5 [0009] In accordance with one aspect of the present invention, a pump includes an actuator formed of a magnetostrictive material susceptible to changes in physical dimensions in the presence of a magnetic field; and first and second pumping chambers coupled to the
10 magnetostrictive element to vary in volume as the magnetostrictive element changes shape.

[0010] In accordance with another aspect of the present invention, a pump includes a housing defining a cylindrical cavity; a cylindrical actuator formed of magnetostrictive
15 material, within the housing and coaxial therewith; first and second pumping chambers within the housing at opposite ends of a lengthwise extent of the magnetostrictive element. Each of the pumping chambers is mechanically coupled to the actuator, to compress as the actuator
20 extends in length.

[0011] In accordance with yet a further aspect of the present invention, a method of pumping fluid using a magnetostrictive element includes, applying a magnetic field to a magnetostrictive element to cause lengthwise
25 extension of the element at two opposing ends; driving a first pumping chamber through the extension of a first end of the two opposing ends; and driving a second pumping

chamber through the extension of a second of the two opposing ends, opposite the first end. Thus, the first pumping chamber is driven in phase with the second pumping chamber.

- 5 [0012] Other aspects and features of the present invention will become apparent to those of ordinary skill in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

10

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] In the figures which illustrate by way of example only, embodiments of this invention:

- 15 [0014] FIG. 1 is a left perspective view of a pump exemplary of an embodiment of the present invention;

[0015] FIG. 2 is a right perspective view of a pump body of the pump of FIG. 1;

[0016] FIG. 3 is an exploded view of the pump body of FIG. 2;

- 20 [0017] FIG. 4A is a cross sectional view of a component of the pump of FIG. 1 taken across lines IVa - IVa;

[0018] FIG. 4B is a cross sectional of a further component of the pump of FIG. 1 taken across lines IVb - IVb;

[0019] FIG. 5A is a right perspective cut away view of the pump body of FIG. 2 along lines V-V;

[0020] FIG. 5B is a right elevational view of FIG. 5A;

5 [0021] FIG. 6A is a further right perspective cut away view of the pumping body of FIG. 2;

[0022] FIG. 6B is a top plan view of FIG. 6A;

[0023] FIGS. 7A and 7B are enlarged sectional views of a portion of the pump body of FIG. 2;

10 [0024] FIGS. 8 and 9 are schematic diagrams illustrating the pump of FIG. 1 in operation; and

[0025] FIG. 10 illustrates a multi pump assembly exemplary of another embodiment of the present invention.

DETAILED DESCRIPTION

15 [0026] FIG. 1 illustrates a pump 10 exemplary of an embodiment of the present invention. Pump 10 is well suited to pump fluids at high flow rates and high pressures. Pump 10 includes few moving parts and is relatively lightweight. It is well suited for use in fuel
20 delivery systems and in particular for use in aircraft engines.

[0027] As illustrated pump 10 includes a single inlet and outlet. As will become apparent, pump 10 includes three

individual pumping chambers housed with a pump body 20. An input manifold 12 distributes a single input to the three chambers. An output manifold 14 combines outputs of the three chambers. A cylindrical connecting pipe 16

5 interconnects pumping chambers. Pipes 18 interconnect pipe chambers to manifolds 12 and 14, and connecting pipe 16 for fluid coupling as illustrated by the arrows in FIG. 1.

[0028] The exterior of pump body 20 is more particularly illustrated in FIG. 2. As illustrated pump body 20

10 includes an outer housing 22 that is generally cylindrical in shape. At its ends housing 22 is capped by threaded clamps 30a and 30b. Three one way flow valves 24a, 26a, 28a near one end of body 20, and three further one way flow valves 24b, 26b, 28b provide flow communication to three
15 separate pumping chambers within pump body 20. As illustrated, in the exemplary embodiment three valves 24a, 26a, and 28a are spaced at 120° about the periphery of housing 22, and extend in a generally radial direction from the center axis of housing 22. Valves 24b, 26b and 28b are
20 similarly situated near the opposite end of housing 22.

[0029] FIG. 3 is an exploded view of pump body 20,

illustrating its assembly. FIGS. 5A, 5B and 6B are

sectional views further illustrating this assembly. As

illustrated, pump body 20 includes a lengthwise extending

25 actuator 32. Preferably actuator 32 is cylindrical in

shape. A multi-turn conducting coil 36 surrounds actuator

32 exterior to ceramic sheath 34. Radially exterior to

coil 36 is a further cylindrical sheath 38. Exterior to

sheath 34 is outer housing 22. Actuator 32, ceramic sheath 34, coil 36, sheath 38 and outer housing 22 are coaxial with a central axis of pump body 20.

[0030] Sheath 38 is preferably formed of a low conductivity soft magnetic material. It may for example be made of ferrite or from laminated or thin film rolled magnetic steel. In the exemplary embodiment, sheath 38 is made from a material made available in association with the trademark SM2 by MII Technologies. Valve seats 40a and 40b are similarly preferably formed of a magnetic material.

[0031] Sheath 38 and valve seats 40a and 40b are preferably formed of a magnetic material, as these at least partially define a magnetic circuit about actuator 32. The choice of materials affects magnetic losses (such as hysteresis and eddy-current losses) in these components.

[0032] Housing 22 is preferably made from a non-magnetic metal such as aluminum, stainless steel, or from a ceramic.

[0033] In the example embodiment, coil 36 is formed from about sixty two (62) turns of 15 awg wire. Of course, the number of turns and gauge of coil 36 is governed by its operating voltage, frequency and magnetic requirements (current).

[0034] As best illustrated in FIGS. 5A and 5B, actuator 32 is held in its axial position within outer housing 22 at its one end as a result of threaded clamp 30a providing an inward axial load on actuator 32 by way of a spacer 39a, valve housing 40a and spacer rings 42a and 44a. At its

other end, actuator **32** is held in its axial position as a result of threaded clamp **30b** providing an inward axial load on actuator **32** by way of a spacer **39b**, valve housing **40b** and spacer rings **42b** and **44b**. Spacers **39a** and **39b** are
 5 generally disk shaped washers formed of a somewhat resilient material, such as a polymer sold in association with the trademark Vespel. Retaining rings **42a** and **44a** (and **42b** and **44b**) are annular nested rings with ring **42a** having a smaller diameter than ring **44a**. The outer diameter of
 10 ring **42a** is about equal to the diameter of actuator **32**. Rings **42a**, **42b**, **44a**, and **44b**, too, are preferably formed of Vespel.

[0035] The spacer rings **44a** and **44b** serve three functions. First, spacer rings **44a** and **44b** act as load springs to
 15 provide an axial pre-load to actuator **32**. Second, they form a seal at each end of the spacer **44a** and **44b**. Thirdly, they partially define pumping chambers **72a** and **72b**, as detailed below.

[0036] Spacer rings **42a** and **42b** similarly serve three
 20 functions. First, they provide radial support to actuator **32** to center it coaxial with cylinder **34**. Secondly, rings **42a** and **42b** seal an annular compression chamber **74**, at valve seats **40a** and **40b** and sheath **34**. Thirdly, an annular manifold for the annular chamber is formed by the space
 25 between the rings **42a** and **44b** (and rings **42b** and **44b**).

[0037] The thickness of spacers **39a** and **39b** are chosen so that when the clamps **30a** and **30b** provide the required axial load on actuator **32** as clamps **30a** and **30b** are tightened

completely to their mechanical stop. Essentially they are also used as springs. Conveniently spacers **39a** and **39b** also provide an insulated hole through which leads to coil **36** may be passed. Spacers **39a** and **39b** could of course, be replaced by a suitable washer.

[0038] Valve housings **40a** and **40b** seat valves **24a**, **26a**, **28a** and **24b**, **26b**, **28b** and provide flow communication between these valves and pumping chambers, as described below.

[0039] In the described embodiment of pump **10**, actuator **32** has about a **0.787"** diameter and a **4.00"** length. Sheath **38** has **1.740"** outside diameter, and a **1.560"** inside diameter. Housing **22** has a total length of about **8.470"**. Sheath **34** has an inner diameter of about **.797"** and is about **4.350** in length.

[0040] Valves **24a** **24b**, **26a**, **26b**, **28a** and **28b** are conventional high speed check valves preventing flow into associated pumping chambers, capable of operating at about **2.5 KHz**. These valves may, for example, be conventional Reed valves. The pressure drop required to open valves **24a** **24b**, **26a**, **26b**, **28a** and **28b** is preferably less than one (**1**) psi and the withstanding pressure (in the opposite direction) is over **2000 psi**.

[0041] Exemplary manifolds **12** and **14** (**FIG. 1**) are identical in structure illustrated in cross-section in **FIG. 4B**.

Manifold **12** acts as an intake manifold and is thus interconnected with inlet valves **24a** and **28a**. Manifold **14** acts as an output manifold, and is thus interconnected to

outlet valves **24b** and **28b**. As illustrated in **FIG. 4B**, manifolds **12** and **14** each include an axial passageway **50** connecting two openings **52a** and **52b** in a cylindrical body **54**, near its ends. Passageway **50** provides flow communication between these openings **52a**, **52b**. Openings **52a** and **52b** are spaced for interconnection between valves **24a** and **24b** or valves **28a** and **28b** (**FIG. 1**). Additional openings **56** permit interconnection of pipes **18** to passageway **50**. Preferably, manifolds **12** and **14** are machined from a hard material such a metal (e.g. stainless steel, brass, copper, etc.).

[0042] Exemplary pipe **16** is similarly illustrated in cross section in **FIG. 4A**. As illustrated, pipe **16**, includes two axial passageways **60a** and **60b** within an outer, generally cylindrical body **58**. Each passageway interconnects and opening **64a** or **64b** for interconnection with valves **26a** and **26b** (**FIG. 1**). Two additional openings **66** (only one shown) are spaced 90° from each other about the central axis of cylindrical body **58**. Openings **66** allow interconnection of pipes **18** (**FIG. 1**) for flow communication with one of passageways **60a** and **60b**. Pipe **16** may be machined in a manner, and from a material similar to manifolds **12** and **14**.

[0043] Pumping chambers within pumping body **20** are more particularly illustrated in **FIGS. 5A, 5B, 6A** and **6B**. **FIGS. 5A** and **6A** are sectional views of pump body **20**, illustrating its three pumping chambers **72a**, **72b** and **74**. **FIG. 5B** is a right elevational view of **FIG. 5A** (and therefore a cross-sectional view of pump body **20**). **FIG. 6B** is a top plan view

of **FIG. 6A**. As illustrated, two end pumping chambers **72a** and **72b** are generally cylindrical in shape, and are located at distal ends of the lengthwise extent of actuator **32**. Preferably, they are located directly between valve housing **40a** and actuator **32**, and valve housing **40b** and actuator **32**, respectively. They are defined in part by opposite flat ends of actuator **32** and flat ends of valve housing **40a** and **40b**. A further axial pumping chamber **74** is located between the exterior round surface of actuator **32**, and an interior cylindrical surface of sheath **34**. Axial pumping chamber **74** extends axially along the length of actuator **32**, and is sealed at its ends by rings **42a** and **42b**.

[0044] As illustrated in **FIGS. 5A** and **5B**, axial pumping chamber **74** is in flow communication with valves **26a** and **26b**, by way of passageways **76a** and **76b** formed in valve housings **40a** and **40b**. Valve housing **40b** is identical to housing **40a** and is illustrated more particularly in **FIG. 7A**. As illustrated an annulus between rings **42b** and **44b** isolates end chamber **72b** from axial chamber **74** and further provides flow communication from chamber **74** through passageway **76b** to valve **26b**. As will become apparent, fluid may thus be pumped from valve **26a** through chamber **74** and out of valve **26b**.

[0045] Cylindrical chamber **72b** is in flow communication with valves **24b** and **28b**, by way of passageways **78b** formed within valve housing **40b**. As such, valve **24b** and valve **28b** act as inlet and outlet valves for end pumping chamber **72b**. Valves **24a** and **28a** similarly serve as inlet and outlet valves, respectively, for pumping chamber **72a**, as

illustrated in **FIG. 6A** and **6B**.

[0046] Actuator **32** is preferably a cylindrical rod, formed of a conventional magnetostrictive material such as Terfenol-D (an alloy containing iron and the rare earth metals terbium and dysprosium). As understood by those of ordinary skill, magnetostrictive materials change shape in the presence of a magnetic field, while, for all practical purposes, retaining their volume. Actuator **32**, in particular, expands and contracts in a direction along its length and radius in the presence and absence of a magnetic field.

[0047] Rings **38** loaded by the force of threaded clamps **30a** and **30b** compress actuator **32** so that in the absence of a magnetic field, actuator **32** is contracted lengthwise. In the presence of a magnetic field actuator **32** lengthens in an axial direction, against the force exerted by rings **38**. All the while the volume of actuator **32** remains constant. As such, an axial lengthening is accompanied by a radial contraction of actuator **32**.

[0048] The expansion of actuator **32** in the presence of a magnetic field is a complex function of load, magnetic field and temperature but may be linear over a limited range. The expansion of Terfenol-D is in the range of **1200** to **1400** parts per million under proper load conditions and optimum magnetic field change. Example actuator **32**, which is about **4"** long, will expand about **.0056"** along its length while contracting in diameter about **.00055"** (static diameter is **.787"**).

[0049] Operation of pump 10 may better be appreciated with reference to the schematic illustration of pump body 20 depicted in **FIGS. 8** to **9**. In operation, a source of alternating current (AC) source of electric energy 80 is applied to lead of coil 36. The frequency for example of the applied current could in this case be 1.25 Khz resulting in this arrangement of a lengthwise contraction expansion frequency of 2.5 Khz (the rod will expand with either polarity of applied magnetic field). Coil 36, in turn, generates an alternating magnetic field with flux lines along the axis of actuator 32. Sheath 38 forms a magnetic guide causing flux generated by coil 36 to be directed into and out of the ends of the rod, through valve seats 40a and 40b.

[0050] Conveniently, eddy current losses kept at a minimum in housing 22 and the valve seats 40a and 40b.

[0051] A fluid to be pumped is provided by way of the inlet of pump 10 (**FIG. 1**), pipes 16, and 18, and inlet manifold 12. Sheath 38 (**FIG. 4**) electrically insulates pump 10, so that current carried by coil 36 does not create substantial electromagnetic interference beyond housing 22.

[0052] As a result of the varying magnetic field generated by coil 36 and source 80, the shape of actuator 32 oscillates between a first state as illustrated in **FIG. 8**, and a second state as illustrated in **FIG. 9**. Transitions between these two states, in turn, cause changes in volume of pumping chambers 72a, 72b and 74, allowing these to act as positive displacement pumps.

[0053] As sheath 34 is made of a hard material such as ceramic, a radial expansion of actuator 38 and resulting displacement of the fluid within cavity 74 is resisted by sheath 34.

5 [0054] Specifically, as illustrated in exaggeration in FIG. 8, in a first state, actuator 32 has a minimum length and a maximum diameter. Chambers 72a and 72b, in turn, have increased volumes, resulting in reduced pressures therein, allowing passage of liquid through valves 24a and 24b, and
10 preventing flow of liquid through valves 28a and 28b. Liquid may thus be drawn into chambers 72a and 72b. At the same time, the volume of chamber 74 is reduced, and liquid therein is displaced by actuator 32. One-way valve 26a remains closed, while valve 26b is opened, allowing fluid
15 to be expelled from axial chamber 74.

[0055] As current flow of the source 80 varies, actuator 32 begins to expand axially and contract radially. One quarter period of oscillation of the electric source later, actuator 32 is in a second state, as illustrated in
20 exaggeration in FIG. 9. In this state, actuator 32 has maximum length, and minimum diameter. As the length of actuator 32 increased it, in turn, displaces fluid in chambers 72a and 72b, increasing the pressure therein. At the same time, the volume of chamber 74 increases as a
25 result of the radial contraction of actuator 32. The pressure in chamber 74, in turn, decreases. Valves 24a and 24b are closed, and valves 28a and 28b are open, allowing liquid to be expelled from chambers 72a and 72b through

valves **28a** and **28b**. Similarly, valve **26a** is opened and valve **26b** is closed. Effectively, the pumping cycles of chamber **72a** and **72b** are in phase with each other, and **180°** out of phase with chamber **74**.

5 **[0056]** For example pump **10**, the total change (i.e. between minimum and maximum diameters of actuator **32**) in the volume of axial pumping chamber **74** is **002724** cubic inches. As the annular chamber **74** expands and contracts twice in each cycle twice this volume could be displaced if there is
 10 little or no leakage and little or no compression of the working fluid. Thus, the displacement volume of chamber **74** is **.00274** cubic inches per cycle of the actuator. Combining the displacement of chamber **74** with chambers **72a** and **72b** results in a total pump displacement of **.0054** cubic
 15 inches per cycle of actuator **32**. Thus at an excitation frequency (in the coil) of **1.25 KHz** (corresponding to an actuator cycle frequency of **2.5 KHz**) results in displacement of **2.5KHz * .0054 cu in = 13.62** cubic inches per second or about **0.223 L/s**. Thus, chambers **72a**, **72b** and
 20 **74** may produce a combined flow of up to about **1300** liters per hour at up to **4000** psi.

[0057] The pressure delivery of the pump depends on the compressibility of the pumped fluid as the cycle to cycle displacement is relatively small. However the pressure
 25 available from the Terfenol is in excess of **8000** psi. Although impractical, if the fluid were not compressible the above noted flow rate previously calculated at **8000** psi might be realizable under ideal non leakage conditions. A

practical result is expected to be up to 4000 psi at flow rates of up to 0.12 L/s for a single pump chamber.

[0058] Conveniently, pipes 16 and 18, and outlet manifold 14 join the output of pumping chambers 72a, 72b and 74

5 allowing these to act in tandem. Advantageously, as chambers 72a and 72b are 180° out of phase with pumping chamber 74, interconnection of the three chamber provides a smooth pumping action, with two compression cycles for every cycle of actuator 32. Additionally, location of
10 pumping chambers around the entire outer surface of actuator 32 allows forces within pump 10 to be balanced, reducing overall vibration of pump 10, during operation. Specifically, as the pressure of pumped fluid is equal all round actuator 32, net side forces are eliminated as a
15 result and lateral vibration of the actuator 32 is reduced. The forces on actuator 32 due to pressure in the axial direction are balanced because the pressures from which the axial cavities are charged and discharged are the same because they are connected together and the end cavities
20 are in phase.

[0059] More significantly, however, are the vibrational forces. If actuator 32 were fixed at one end, the acceleration forces related to the vibration of the actuator are reacted at the one end resulting in inertially
25 related vibrations. In pump 10 two opposite ends of the actuator 32 accelerate in equal and opposite directions resulting in equal and opposite inertial forces which cancel. This results in a balanced system resulting in

significantly less vibration and noise than could be obtained in conventional imbalanced arrangements.

[0060] FIG. 10 further illustrates a multi-pump, pump assembly 100 including a plurality (three are illustrated) of pumps 102, each substantially identical to pump 10 (FIG. 1). As illustrated, pipes 18 interconnect pumps 102. Inputs and outputs of pumps 102 are connected in parallel. Pump assembly 100 may be beneficial if higher flow rates are required.

[0061] Conveniently, each pump of the pump assembly 100 may be driven out of phase from the remaining pumps. For example, for a three pump assembly, each pump 102 may be driven from one phase of a three phase power source (not shown), so that each pump 102 further smoothing any pressure fluctuations in output of any pump 102. Additionally this arrangement allows for redundancy as is often required for high reliability systems. Failure of one of the pumps 102 or one of the electrical phases would not cause total loss of flow.

[0062] Pump assembly 100 could similarly be arranged with inputs and outputs of pumps 102 interconnected in series. In this way, each pump 102 would incrementally increase pressure of a pumped fluid.

[0063] As should now be appreciated, the above described embodiments may be modified in many ways without departing from the present invention.

[0064] For example a pump and pump assembly could be

machined and manufactured in many ways. One or more pumps may be cast in a body that does not have an outer cylindrical shape. Fluid conduit from and between pumps could be formed integrally in the cast body. Valves need not be arranged radially at 120° about an axis of an actuator, but could instead be arranged in along one or more axis of a body defining the pump.

[0065] An exemplary pump having only two pumping chambers will provide many of the above described benefits. For example, a pump having only two in-phase chambers (like end chambers **72a**, **72b**) driven by a single actuator may provide a balanced pump, with relatively few moving parts having only a single pumping stroke for a cycle of an actuator. Similarly, a pump having two chambers driven by a single actuator, with each of the pump chambers 180° out of phase with the other may provide relatively smooth pumping action. Of course, a pump having more than three chambers could be similarly formed.

[0066] Of course, a pump embodying the present invention may be formed with many configurations, in arbitrary shapes. For example, the pump assembly, housing and actuator need not be cylindrical. Similarly, pumping chambers need not be directly defined by a magnetostrictive element. Instead, an actuator may be mechanically coupled to the pumping chambers in any number of known ways. For example, the pumping chamber could be formed of a bellows driven a magnetostrictive actuator.

[0067] All documents referred to herein, are hereby

incorporated by reference herein for all purposes.

[0068] Of course, the above described embodiments, are intended to be illustrative only and in no way limiting.

The described embodiments of carrying out the invention,

5 are susceptible to many modifications of form, arrangement of parts, details and order of operation. The invention, rather, is intended to encompass all such modification within its scope, as defined by the claims.